# Brilliance Scaling of Discharge based EUV and soft X-Ray Sources

Klaus Bergmann, Fraunhofer Institute for Laser Technology, Aachen, Germany

Source Workshop, 13-15 November, Dublin



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# Overview

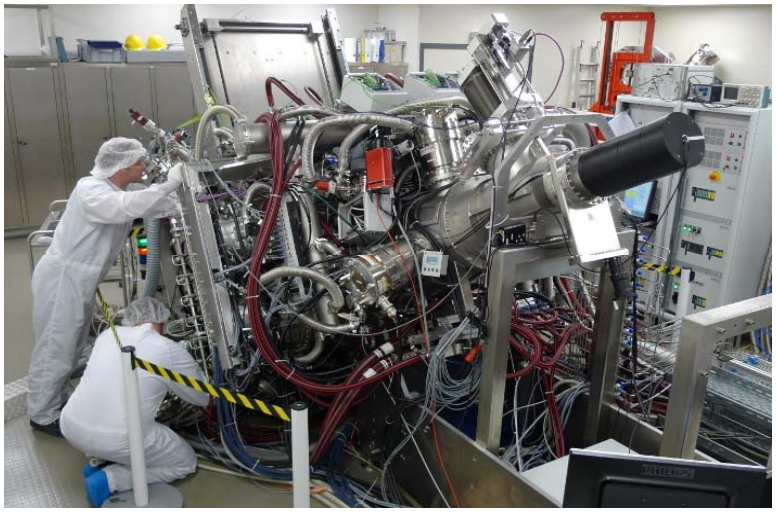
- Introduction
- Investigations on brilliance for pseudo-spark based discharge source at ILT
- State of the art for:

| | | |
|---|---|---|
| 2.9 nm | into single line | : soft x-ray microscopy |
| 10.9 nm | into 4% b.w. | : interference lithography |
| 13.5 nm | into 2% b.w. | : environment of EUV lithography |

- Outlook on brilliance scaling potential
- Conclusions

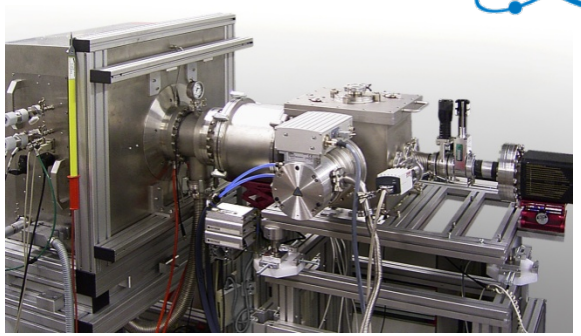
# Current XUV activities at ILT

- Development of sources for EUV lithography based on tin vacuum arc (together with Xtreme)
- Sources for metrology in the range soft x-ray and EUV
- XUV-Applications **(*)**
  (Support of TOS, RWTH Aachen University)

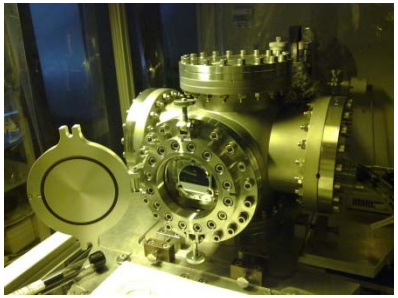


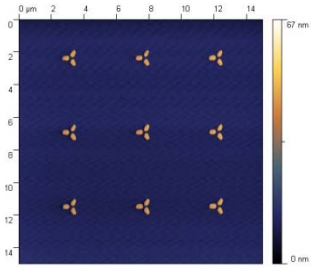
EUVL source development

X-ray microscopy



Interference lithography

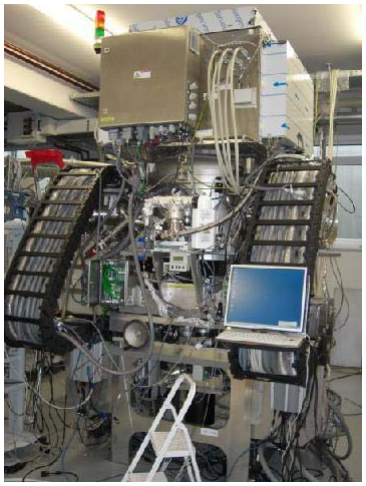






**(*)** see also posters on “Defect Inspection”, ”Reflectometry” and ”Interference Lithography” by Larissa Juschkin

# Discharge XUV sources are in commercial use . . .

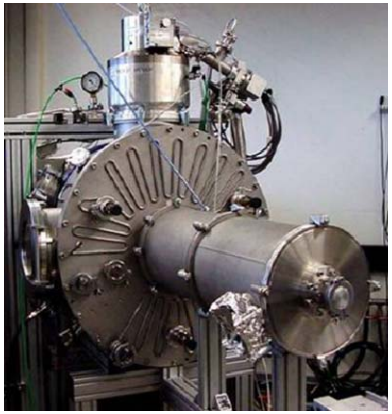


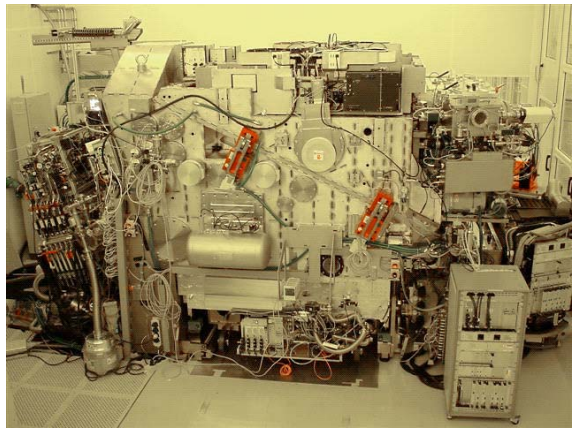
XTREME technologies

USHIO GROUP

AIXUV EUV-Technology

BRUKER





PHILIPS





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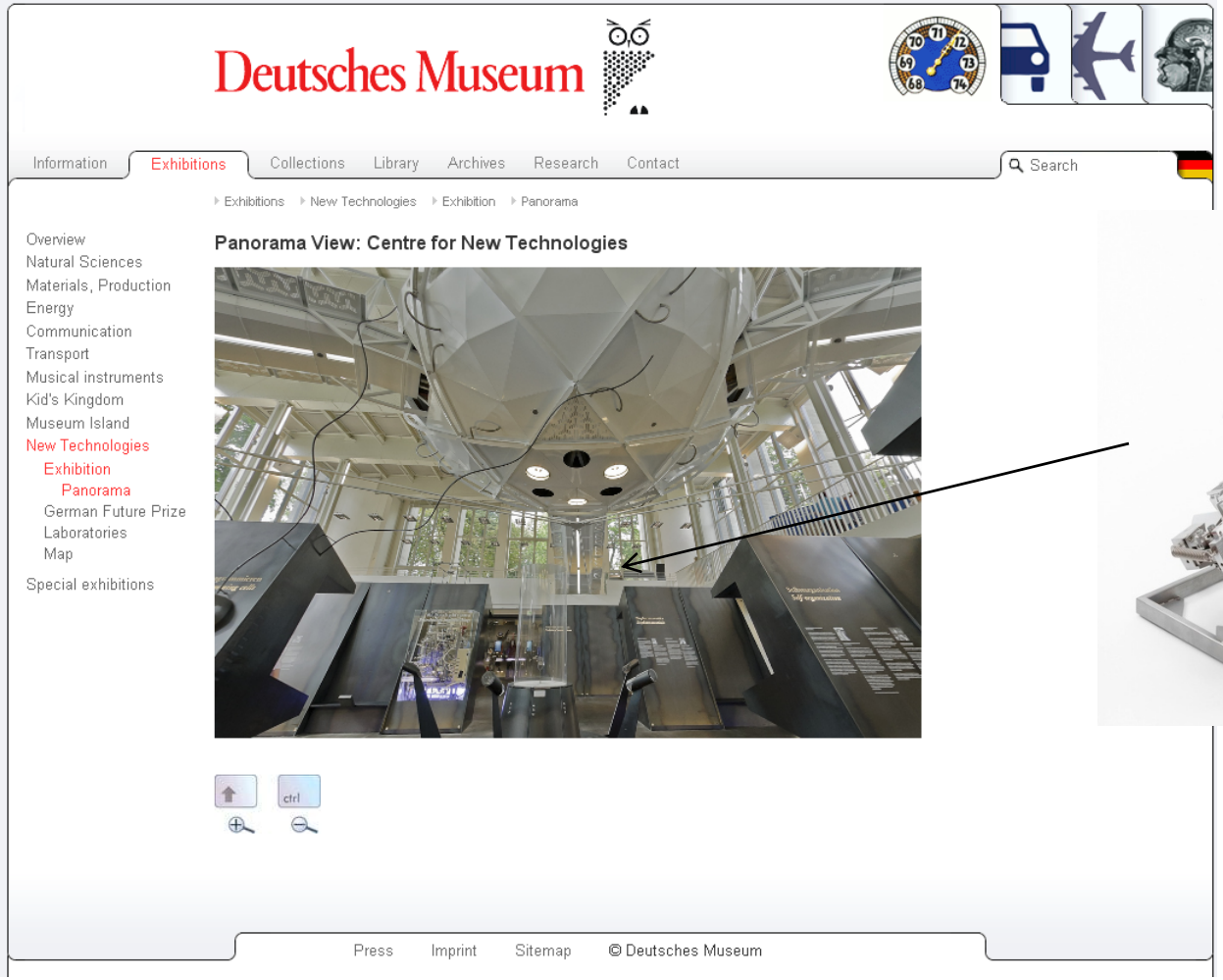
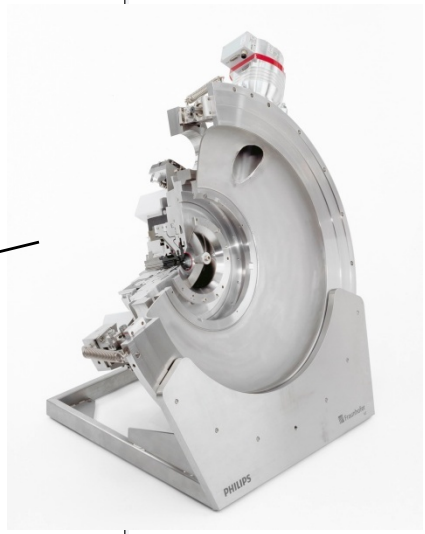
# …and also already in museum

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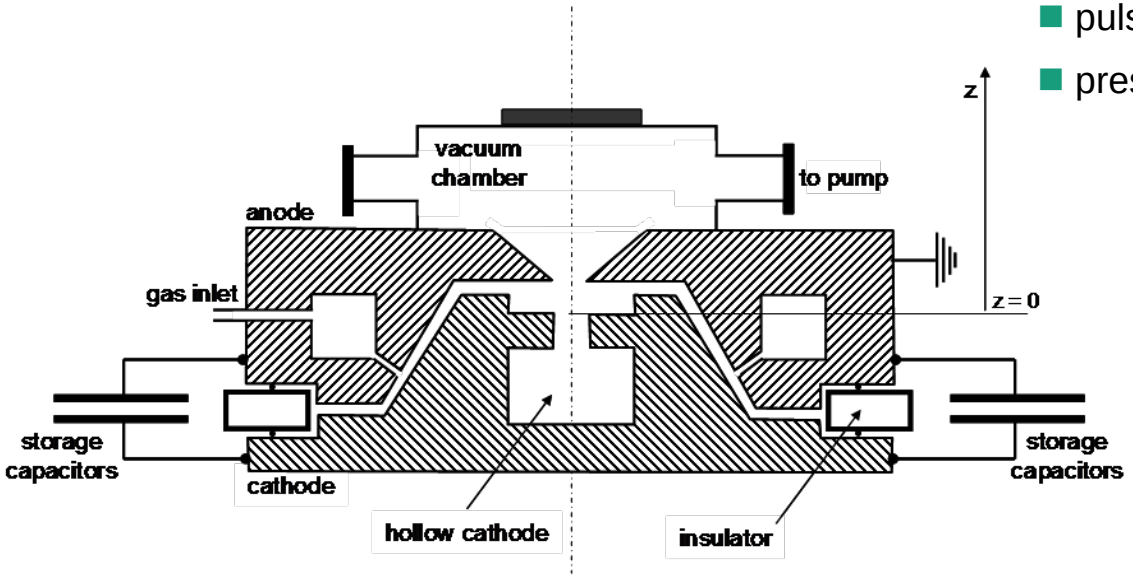
http://www.deutsches-museum.de/en/exhibitions/new-technologies

# Pseudospark based discharge source

## Typical device parameters

- capacity : 100 nF to few µF
- pulse energy : 2 - 20 J
- inductance : ~ 10-14 nH
- peak current : up to 40 kA
- pulse duration : few 100 ns
- pressure : several 10 Pa (dependent on gas)

## Scheme of electrode system





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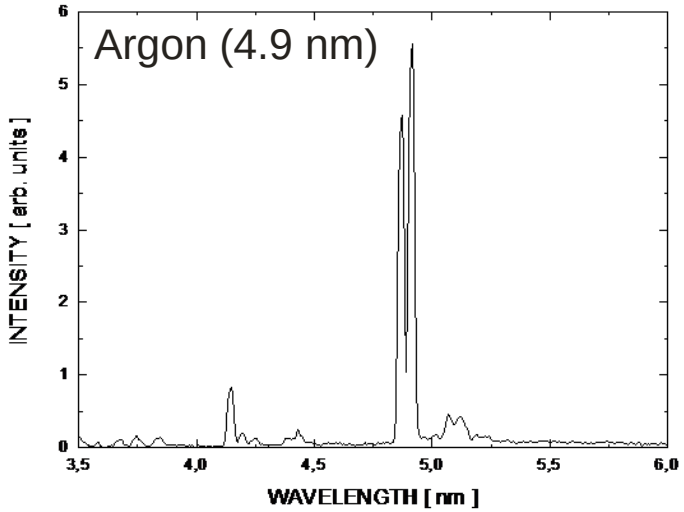
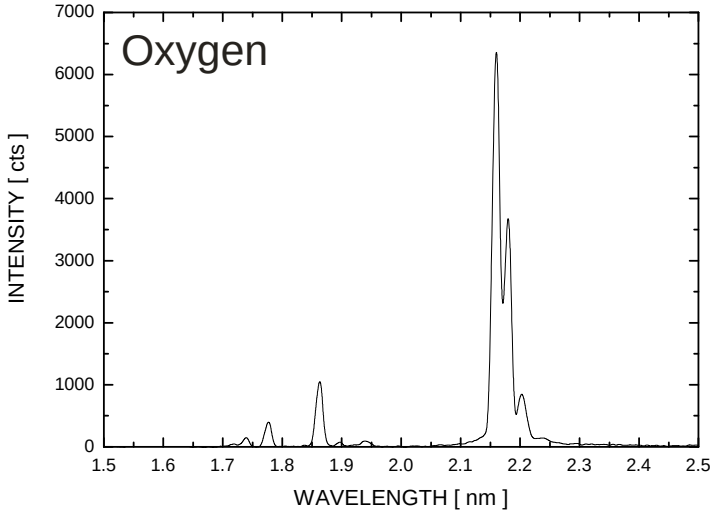
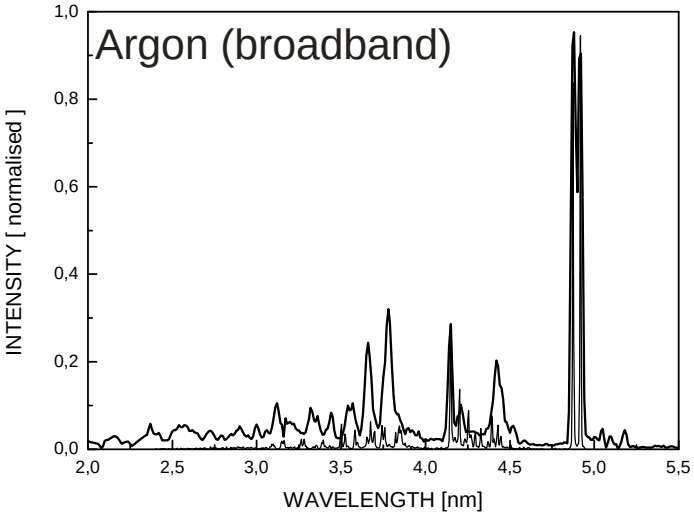
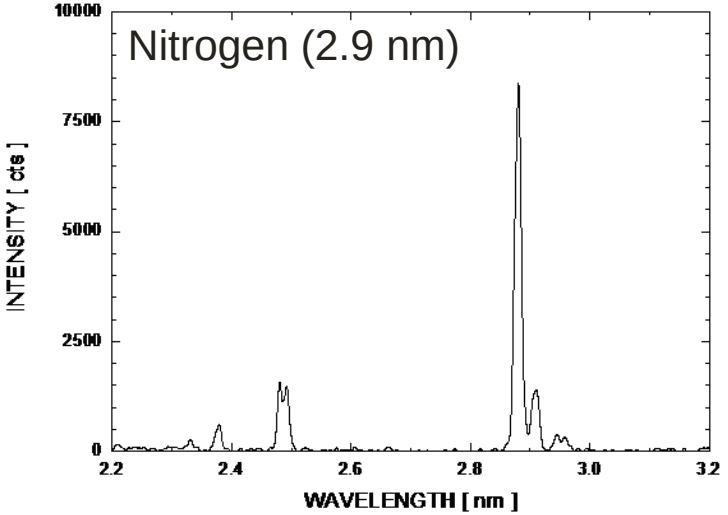
# Emission spectra (soft x-ray)





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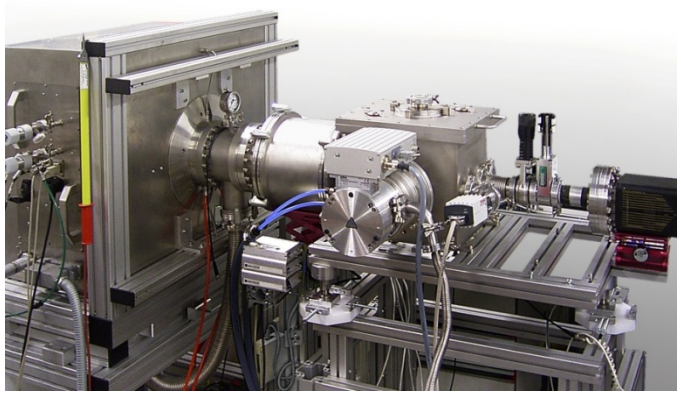
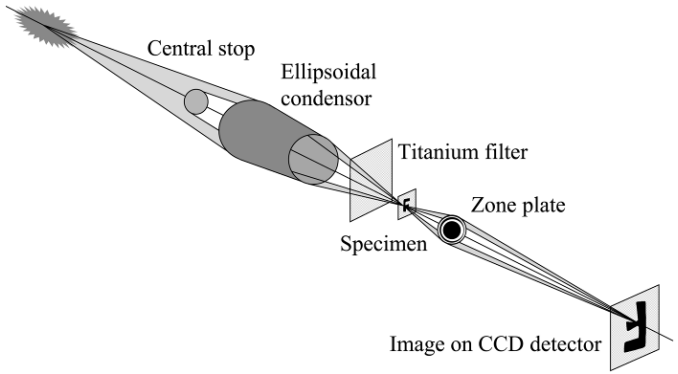
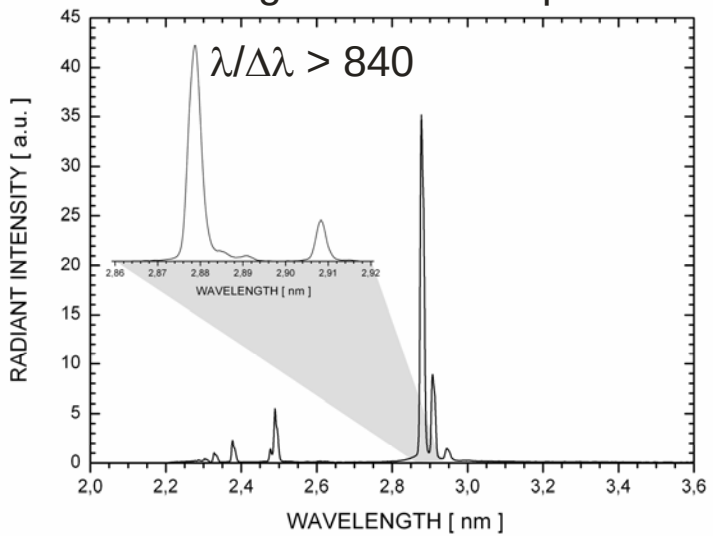
# Soft x-ray microscopy

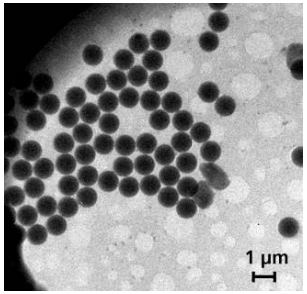




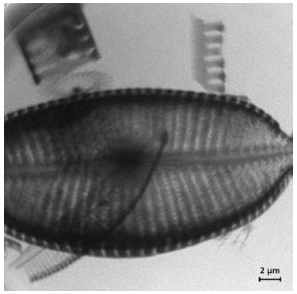

Nitrogen emission spectrum



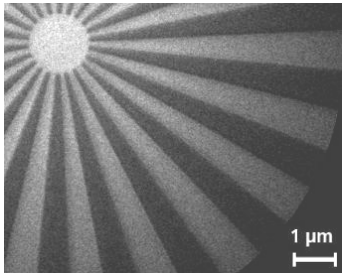

- brilliance : $2*10^9$ Ph/(µm$^2$ sr s)
- total emission: 15 W/(2πsr) at 2.88nm (430 eV)
- input power : 20 kW at 1 kHz




Latex-Spheres



Diatoms




Siemens star

# Platform for brilliance measurements (EUV)

- Xenon based technology developed by Philips for EUV lithography
- input power : max. 10 kW
- pulse energy : max. 3 J
- repetition rate : max. 3 kHz
- operational with different gases

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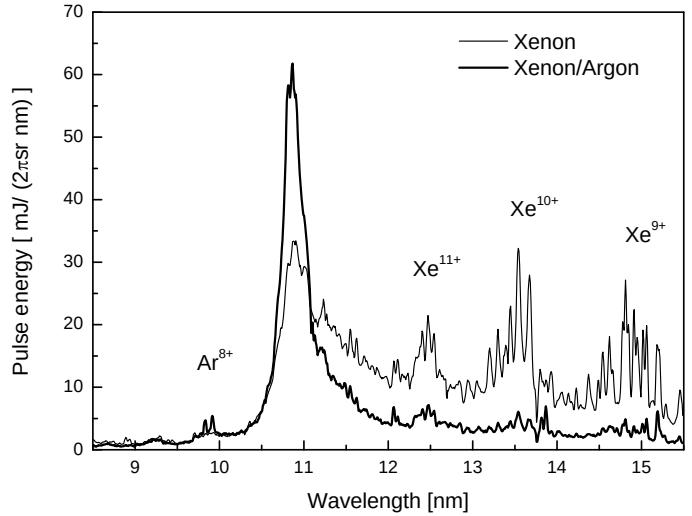
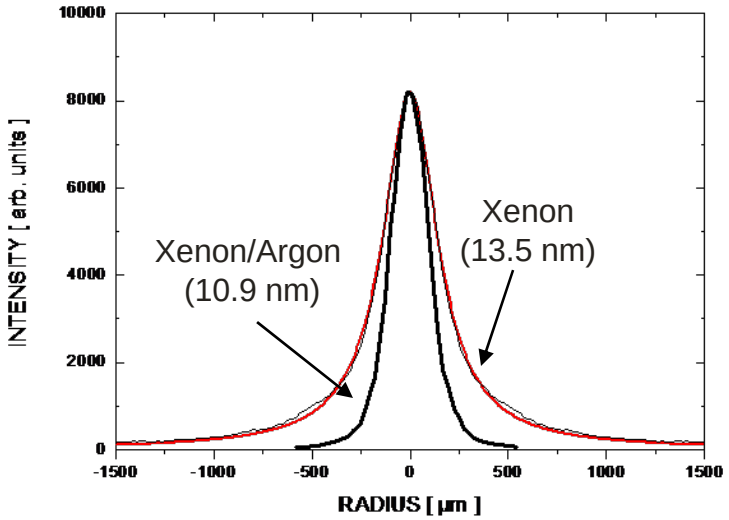
# Brilliance for optimization around 11 nm

- suppression of optically thin Xe transitions by dilution with Argon:
  ~ 11 nm : optically thick 4f-4d transitions
  ~ 12-16 nm: optically thin 5p-4d transitions
- increase of brightness at 11 nm due to better discharge conditions with Argon
- discharge parameters:
  frequency : 2000 Hz
  pulse energy : 2.8 J
  input power : 5.6 kW
- emission around 11 nm into 4% b.w.:
  radius(FWHM): 100 µm
  near Gaussian shape
  total power : **40 W/(2πsr)**
  brilliance : **100 W/(mm²sr)**





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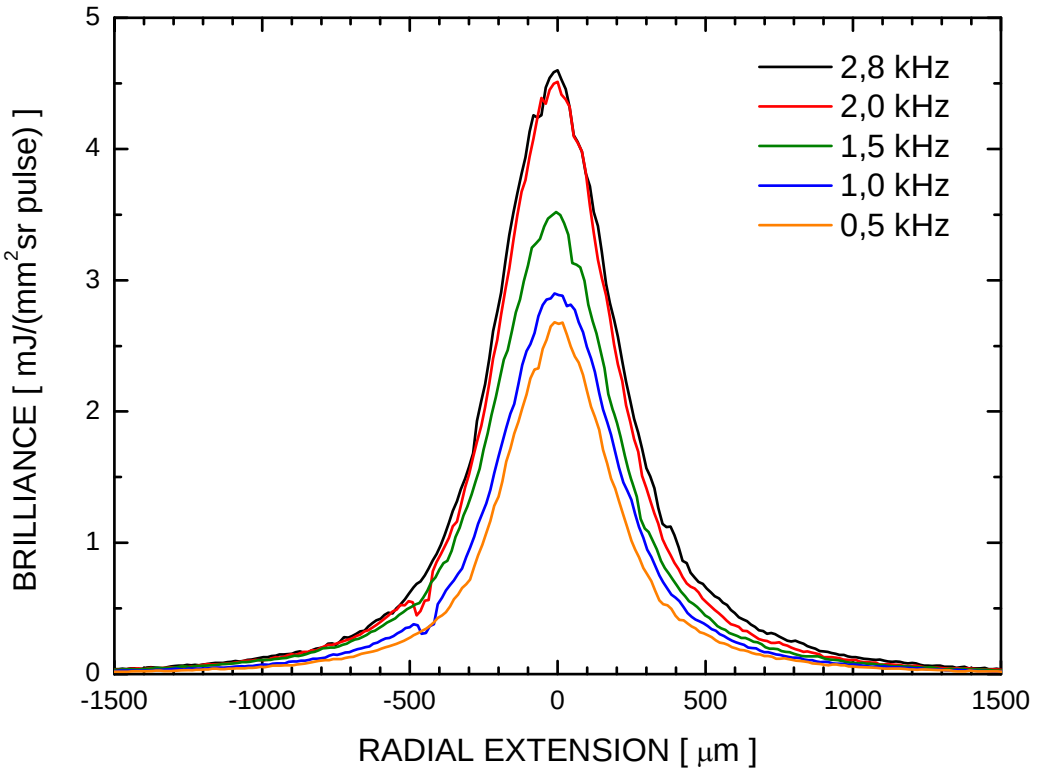
# Measurements around 13.5 nm: Radial Profile

- pulse energy : 3.1 J
- input power : up to 8.7 kW
- no increase of radius with increase of input power
- maximum pulse brilliances at highest input power
- no change of radial profile with input power
- radius (FWHM) : ~ 210 µm





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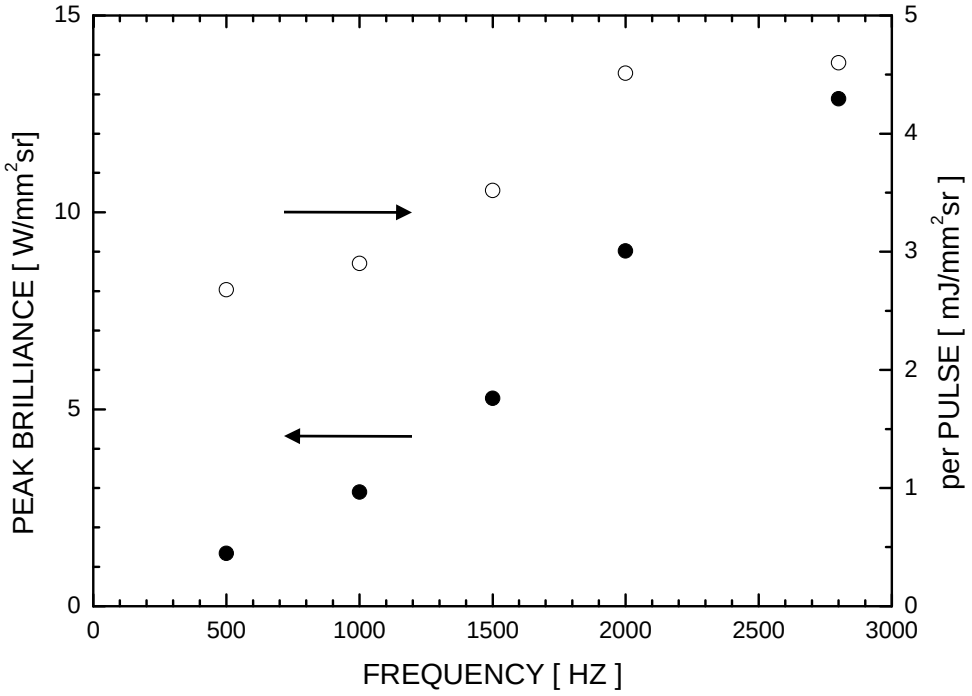
# Measurements around 13.5 nm: Brilliance Scaling

- increase of peak brilliance with higher input power due to higher conversion efficiency
- discharge parameters:
  frequency : 2800 Hz
  pulse energy : 3.1 J
  input power : 8.7 kW
- emission around 13.5 nm into 2% b.w.:

  radius(FWHM): 210 µm
  close to Lorentzian shape
  total power : **48 W/(2πsr)**
  brilliance : **12.9 W/(mm²sr)**





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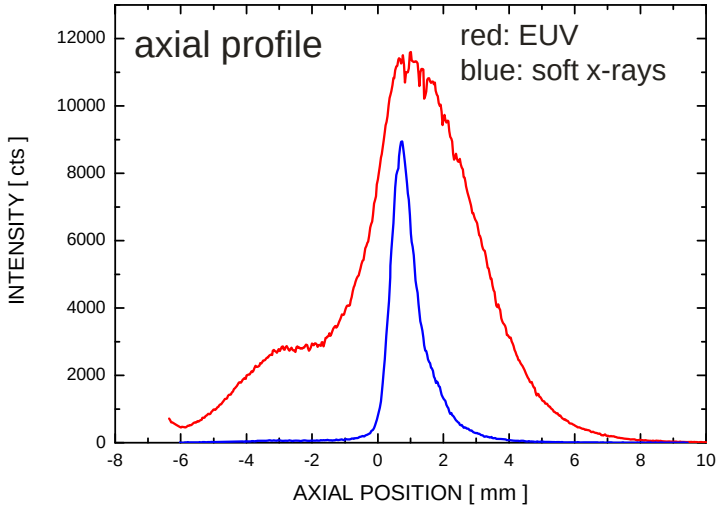
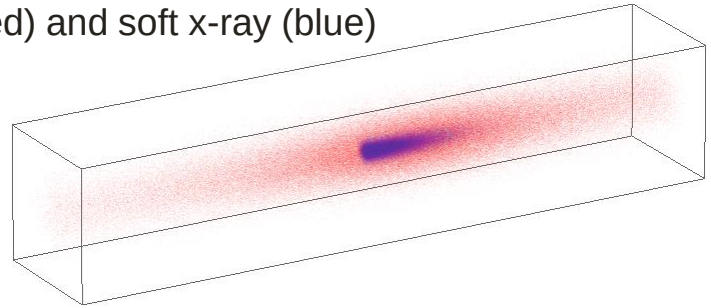
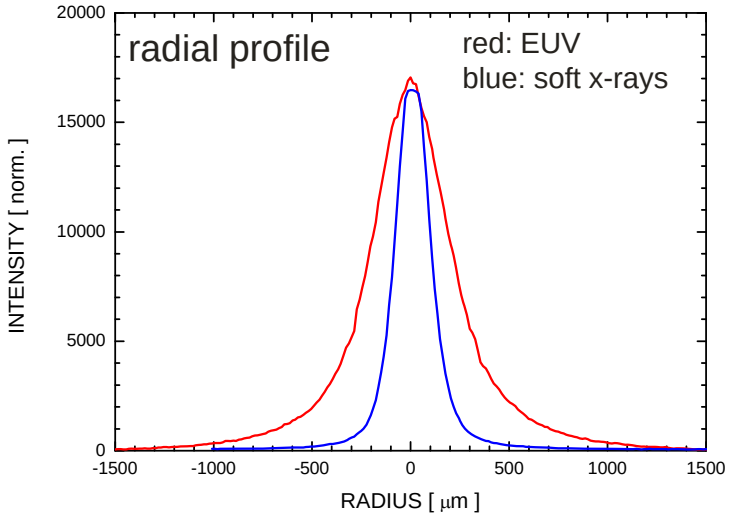
# Xenon discharge: Soft x-ray contribution (1)

- pulse energy : 3,1 J
- pinhole images for
  - soft x-rays (Ti) : ~3 nm
  - EUV($Si_3N_4$ + Zr) : 12-16 nm
- observed hot spot
  - length : ~ 1 mm
  - radius : ~100 µm




Simulated distribution of
EUV (red) and soft x-ray (blue)







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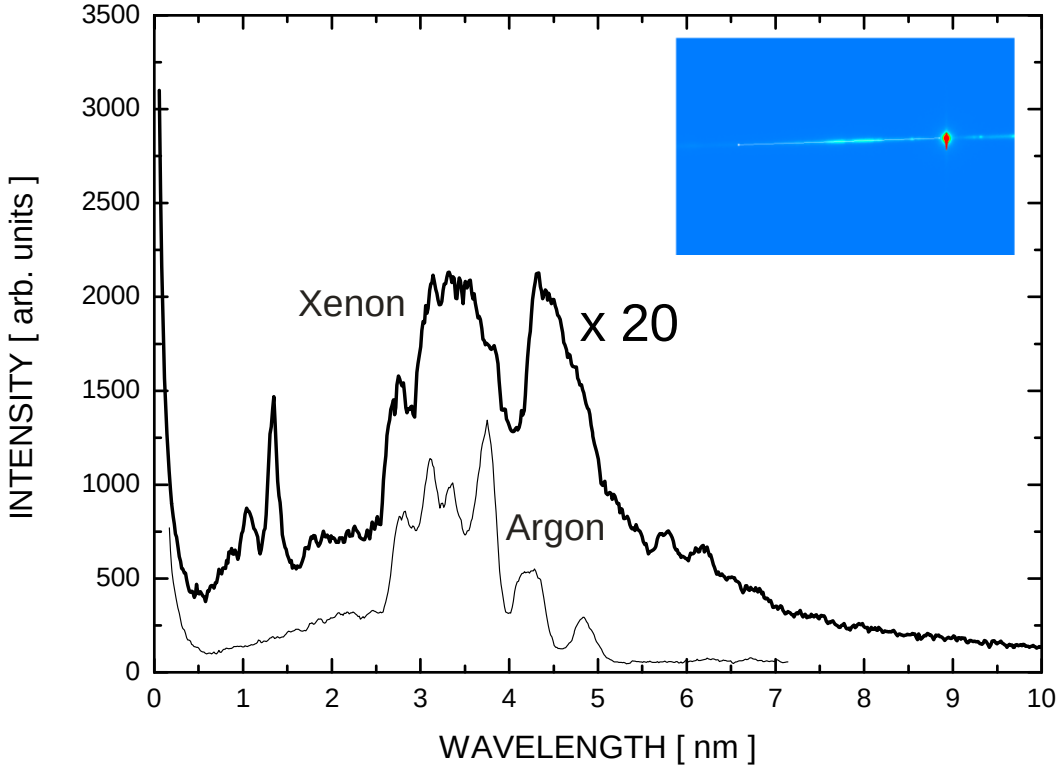
# Xenon discharge: Soft x-ray contribution (2)




- emission spectra observed with pinhole grating spectrograph (low resolution)
- control measurement with Ar
- broadband Xenon emission in water window range
- line emission around 1.4 nm
- hint for highly ionized Xenon and processes leading to small hot spots





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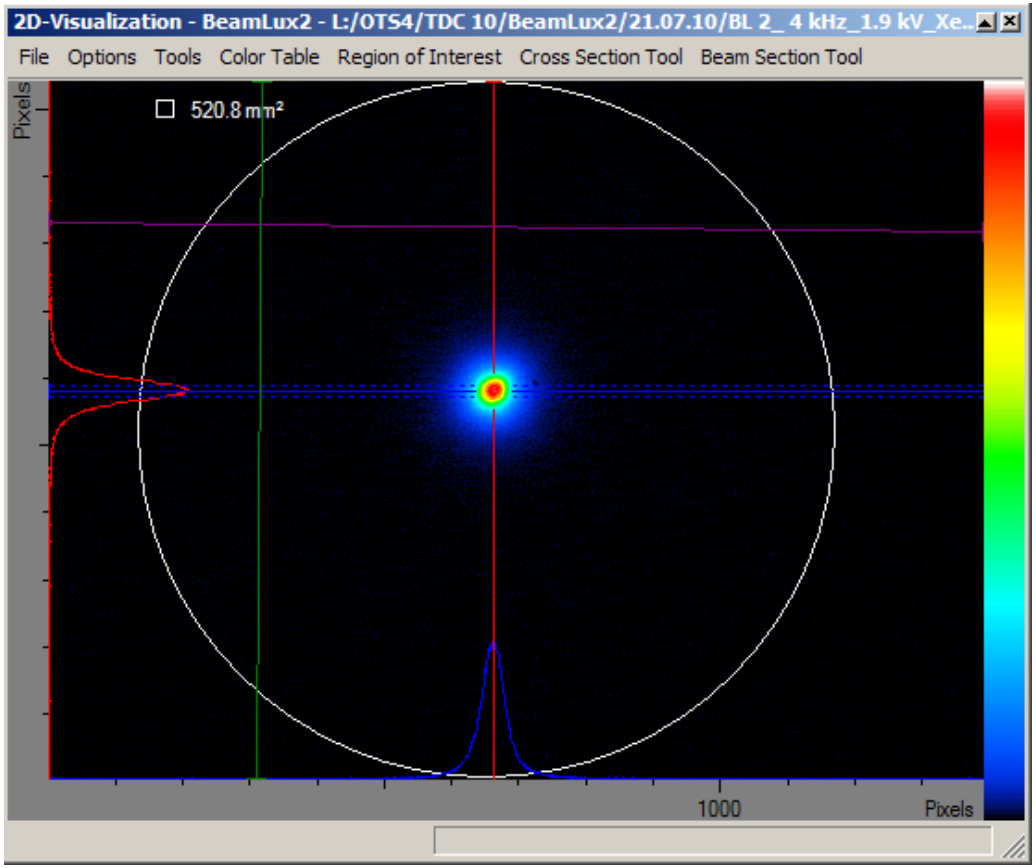
# Brilliance of standard Xenon source at Xtreme




Brilliance B:

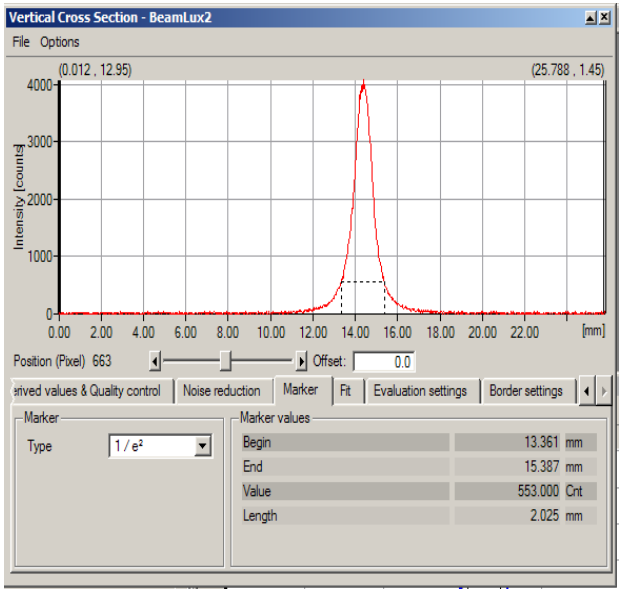
16.5 W / (mm² sr)

into 2% b.w. for 13.5 nm

4 kHz operation , dc ~ 10%

Radial profile (on-axis)

radius (FW1/e²) : ~ 0.8 mm




$$\int B(x,y,)\,dA = 146\ W / 2\pi$$

# Scaling considerations for 13.5nm (2% b.w.)

| | | today | extrapolated | Remark |
|---|---|---|---|---|
| Input Power | kW | 8,7 | 15 | by increase of repetition rate and pulse energy |
| Conversion efficiency | %/(2πsr 2%b.w.) | 0,48 | 0,6 | already observed for different discharge conditions |
| Pinch radius (end-on) | µm | 210 | 170 | 140 µm already observed for different discharge conditions |
| Pinch Profile | | appr. Lorentz | Gauss (gain of ~2) | currently dividing by $3.7\pi r^2$ |
| Loss due to axial extension | | 0,8 | 0,8 | for emission into 2.3° (half cone) |
| Brilliance | W/(mm²sr) | 12,9 | 84.0 | (losses due to axial extension not included) |

Including technical constraints: **~ 40 W/(mm² sr)**
at 13.5 nm into 2% b.w.





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# Next Generation XUV sources at ILT

- same design for covering the range from soft x-rays to extreme ultraviolet
- power supply developed by ILT matched to special requirements for XUV sources
- push-button operation
  ( no special trained personal required)

Lamp Head
(60 cm diameter)

# Conclusions and Summary

- discharge sources exhibit high maturity and are in commercial use
- a range from soft x-ray to extreme ultraviolet can be covered with the same discharge concepts
- work on brilliance scaling just has started
- demonstrated:

  >100 W/(mm$^2$ sr) into 4% b.w. for 10.9 nm (ILT)
  12.9 W/(mm$^2$ sr) into 2% b.w. for 13.5 nm (ILT)
  16.5 W(mm$^2$ sr) into 2% b.w. for 13.5 nm (Xtreme Tech.)

- optimization potential for up to 100 W/(mm$^2$ sr) for 13.5 nm is identified
- discharge sources are worth for further work on brilliance scaling